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Abstract: The ability to charge battery electric vehicles (BEVs) on a time scale that is on par with the time to fuel an internal combustion engine vehicle (ICEV) would remove a significant barrier to the adoption of BEVs. However, for viability, fast charging at this time scale needs to also occur at a price that is acceptable to consumers. Therefore, the cost drivers for both BEV owners and charging station providers are analyzed. In addition, key infrastructure considerations are examined, including grid stability and delivery of power, the design of fast charging stations and the design and use of electric vehicle service equipment. Each of these aspects have technical barriers that need to be addressed, and are directly linked to economic impacts to use and implementation. This discussion focuses on both the economic and infrastructure issues which exist and need to be addressed for the effective implementation of fast charging at 400 kW and above. In so doing, it has been found that there is a distinct need to effectively manage the intermittent, high power demand of fast charging, strategically plan infrastructure corridors, and to further understand the cost of operation of charging infrastructure and BEVs.

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We have electronically submitted a manuscript entitled "Enabling Fast Charging – Infrastructure and Economic Considerations" that we hope to have published in the Journal of Power Sources. The manuscript is part of a set of manuscripts detailing the present issues associated with fast charging of electric vehicles up to 400 kW and is intended to be a part of the Special Issue: Fast Charging of Batteries. The paper looks at identifying economic and infrastructure limitations that need to be addressed as part of the roll out of fast chargers for electric vehicles up to 400 kW. This includes better routes to deal with demand charges, considering the total cost of ownership of a fast charge capable vehicle and the installation and operational costs associated with high power vehicle chargers.

As part of a joint effort to identify limitations to fast charging, the manuscript references (1, 2 and 3) the other efforts in batteries, thermal management and pack design and vehicle limitations. These three manuscripts have not been published to date, but will be submitted to the same special issue. Additionally, the manuscript references a report which is currently under review at the US Department of Energy (reference 29). This review should be completed prior to publication. If not the text will be adjusted accordingly and the manuscript will be resubmitted for review of any resulting changes.

My address, email and fax are listed above, and I will be the corresponding author. We accept any page charges associated with publication of the paper. Original figures are electronic in .jpg form. Please let me know if there is anything else I need to do with regard to this submission.

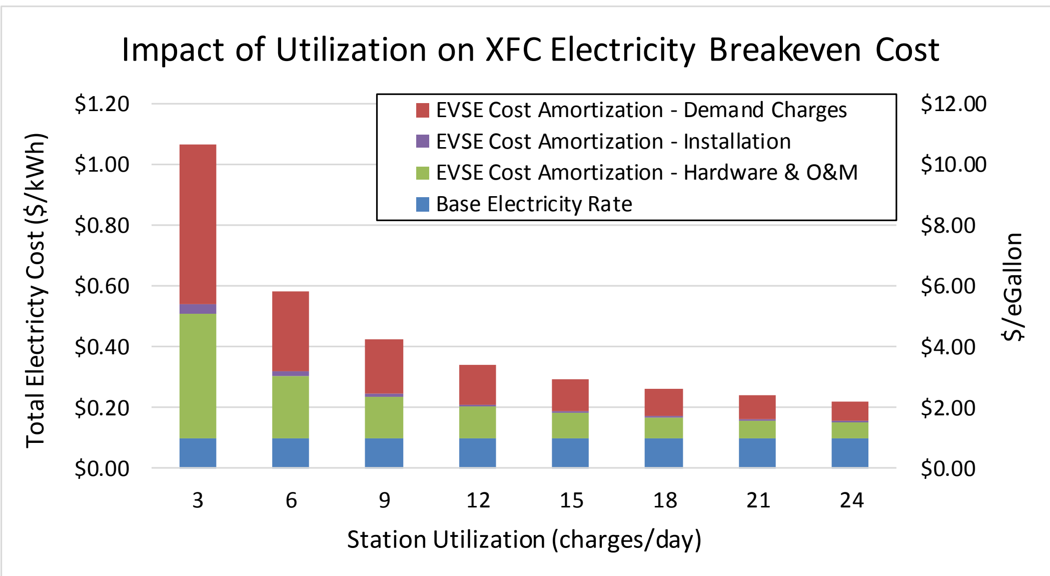
Sincerely,

Eric J. Dufek, PhD

***Highlights (for review)**

Highlights:

- Management of intermittent, high power demand is crucial, especially at low utilization
- Planning is needed for XFC including siting future corridors
- Cost of the charging equipment and its installation and operation must be accounted for in planning
- Increased coordination needs to occur between governing authorities
- Safety, cyber physical security, interoperability and compatibility will impact utilization



Enabling Fast Charging – Infrastructure and Economic Considerations

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Abstract

The ability to charge battery electric vehicles (BEVs) on a time scale that is on par with the time to fuel an internal combustion engine vehicle (ICEV) would remove a significant barrier to the adoption of BEVs. However, for viability, fast charging at this time scale needs to also occur at a price that is acceptable to consumers. Therefore, the cost drivers for both BEV owners and charging station providers are analyzed. In addition, key infrastructure considerations are examined, including grid stability and delivery of power, the design of fast charging stations and the design and use of electric vehicle service equipment. Each of these aspects have technical barriers that need to be addressed, and are directly linked to economic impacts to use and implementation. This discussion focuses on both the economic and infrastructure issues which exist and need to be addressed for the effective implementation of fast charging at 400 kW and above. In so doing, it has been found that there is a distinct need to effectively manage the intermittent, high power demand of fast charging, strategically plan infrastructure corridors, and to further understand the cost of operation of charging infrastructure and BEVs.

Keywords: Extreme Fast Charging (XFC), Electric Vehicle Infrastructure, Battery Electric Vehicles, Demand Charges, Total Cost of Ownership, Economics

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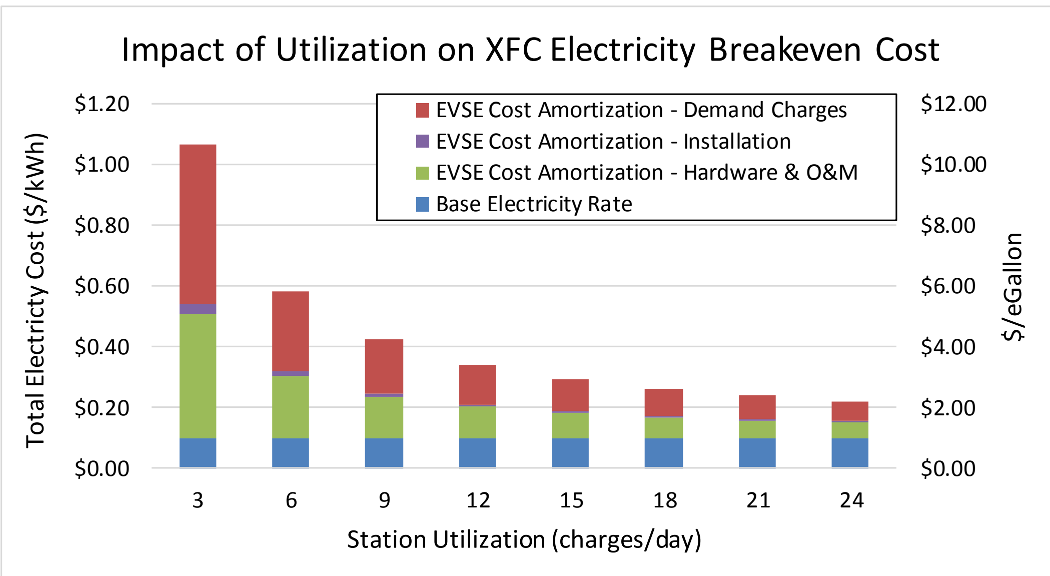

1. Introduction

The push to reduce the charging time needed for plug-in battery electric vehicles (BEVs) creates a suite of intertwined research, development and deployment (RD&D) challenges. In addition to the RD&D challenges for vehicles and battery technologies that have been described elsewhere [1] [2] [3], there is a distinct need to understand how extreme fast charging (XFC) with powers of 400 kW and above will impact the electrical grid, the use of electric vehicle service equipment (EVSE), corridor planning and ultimately how the cost of ownership and deployment economics evolve.

Both BEVs and internal combustion engine vehicles (ICEVs) require specific and unique forms of infrastructure for refueling. In the case of ICEVs, there is an expansive network of refueling stations that already exists. For BEVs, the options are more disparate including residential charging, work place charging, and the use of a still emerging public charging infrastructure including both alternating current (AC) Level 2, and direct current (DC) fast charging (DCFC) [4]. The range of charging options present both challenges and opportunities as the adoption of BEVs continues to increase [5]. One distinct opportunity that exists is the ability to logically plan the infrastructure for the BEV fleet including the placement of DCFC above 50 kW and up to 400 kW in metro areas and travel corridors.

Higher power charging systems which operate up to 400 kW and could replace 200 miles in 10 minutes of recharging, look to address what some perceive as limitations with BEVs including: length of time to charge and overall BEV range [6]. Public fast charging could increase BEV market penetration by allowing consumers who do not have access to either residential or workplace charging to use it as their primary means of charging. The use of BEVs in commercial applications such as taxi, ride-share, or car-share services, where vehicles are heavily utilized could be enabled due to the added convenience of fast charging. In addition, higher power charging would make long-distance, intercity travel more practical for BEVs by making refueling times similar to ICEVs.

Presently most BEV users charge at home followed by work place charging [7]; however, early evaluations of the impact of DCFC up to 50 kW highlights the added flexibility that the faster charging gives to BEV users. One example of the positive impact on travel distance was identified in a study that followed Nissan Leafs which either used or did not use DCFC (up to 50 kW) [8]. With the use of DCFC (up to 50 kW), it was observed that longer range trips using BEVs have occurred in the northwestern portion of the United States. Indeed, the use of DCFC has increased the number of trips that extend beyond the centralized metropolitan centers of Seattle, Washington and Portland, Oregon. The extended range provided by DCFC allowed more trips to the Oregon and Washington coast and into the Cascade mountain range. While the data is not presently available it is expected that similar impacts would be observed for other regions of the country and the world. The ability to use DCFC for longer trips, combined with automotive manufacturers producing a greater number of BEVs with range above 100 miles, can help minimize, but not fully remove the ‘range anxiety’ gap that exists, for some users, between ICEVs and BEVs.

Current DCFC systems do not offer BEV consumers nearly the same refueling experience as gasoline ICEV consumers. Replacement of more energy in a shorter period of time is one of the ways that the gap between ICEVs and BEVs can be further bridged. Extreme fast charging with powers at 400 kW or higher would enable a significant replacement of driving range in a period of 10 to 25 minutes. For the present work XFC is defined as the replacement of at least 20 miles per minute. At these rates it is conceivable that 200 miles of range could be replaced in 10 minutes of charging. In addition to replacing significant driving range, for XFC to be viable it must be at price that customers are willing to pay. As such, it is necessary to understand a host of interactions for XFC that occur at the grid and EVSE level as well as the business case of XFC infrastructure. In the discussion below key uncertainties and the related RD&D needs are highlighted including; installation and operational cost of XFC EVSEs, the purchase and operational cost of XFC-capable BEVs, market opportunities, planning and stakeholder education, and management of intermittent load profiles likely to arise from XFC stations.

2. Review of Key Considerations of XFC Infrastructure and Economics

2.1. Overview of XFC cost drivers

In this section, we detail the cost drivers of XFC from both a vehicle owner and EVSE provider standpoints. The total cost of ownership (TCO) for a vehicle owner is shown in Equation 1.

$$\boldsymbol{TCO} = Vehicle\ (Depreciation) + Maintenance\ \&\ Repair + Fuel + Insurance + License\ \&\ Registration + Public\ support\ cost + Value\ of\ Travel\ Time \qquad \text{(Eqn. 1)}$$

As shown in Figure 1A, the cost of BEVs using XFC will be heavily influenced by battery costs, while other vehicle costs, such as power electronics and thermal management, may be important as well. Additionally, battery lifetime can impact maintenance and repair costs. For BEVs fuel cost is directly tied to the cost of electricity at the point of sale, which depends on the cost of EVSE infrastructure, demand charges, and station utilization. Indirect costs should also be accounted for including opportunity costs relating to travel time.

The TCO of XFC-capable BEVs can be compared with that of different vehicles to assess the economic feasibility from the owner's perspective and to examine how XFC influences the magnitude of each cost component. Examples of TCO for gasoline ICEVs, gasoline hybrid electric vehicles (HEVs), BEVs solely using DCFC, and BEVs solely using XFC are given in section 2.6.

The simple payback of owning and operating an EVSE are the ratio of upfront costs to total annual costs, as illustrated in Equation 2.

$$Simple\ Payback = \frac{Private\ Capital\ Costs - Public\ Incentives}{Point\ of\ Sale\ Revenue + Indirect\ Revenue - Operation\ \&\ Maintenance\ Costs} \quad \text{(Eqn. 2)}$$

As shown in Figure 1B, the economics of an XFC station heavily depend on the cost of EVSE equipment and installation, electricity costs, demand charges, station utilization, point of sale revenue, and indirect revenue. The key cost drivers for both XFC infrastructure and BEVs are discussed in detail in the following sections.

2.2. Infrastructure costs and considerations

Due to the complex nature of the infrastructure needed for XFC, three different areas were defined for analysis. These include grid and utility needs, charging station needs and EVSE needs. For each area, an issue tree was constructed that defines key areas for consideration that need to be addressed for the successful implementation of XFC. Overarching each issue tree is the need for safety and well-defined codes and standards. Ultimately, for the successful development of codes and standards there needs to be a concerted effort on the part of multiple organizations that include industry and codes and standards bodies such as the National Fire Protection Association (NFPA). To address the safety of XFC, coordination between industry, local authorities and various authorities having jurisdiction (AHJs) and public utility commissions (PUCs) will become important. In conjunction with planning, will be the need for sufficient stakeholder education and engagement.

2.2.1. Utility and planning

2.2.1.1. XFC station siting

Presented in Figure 2A are the potential impacts to grid and utility operation with the implementation of XFC. While extensive fast charging networks are only now starting to emerge, there have been a few isolated studies that hint at the potential grid issues that may arise from larger scale implementation. First, a key concern is that the addition of multiple charging stations will increase the overall power demand and that the hardware will create grid instabilities. Some support of this concern has been found where current BEV fast charging stations have been seen altering the steady state voltage stability of the grid [9] [10]. Others studies have found that harmonic limits need to be considered as much as the limits set on power to the EVSE [11]. Additional grid stability issues associated with high BEV adoption have also been identified, including enhanced aging of transformers related to the shortened life of insulation, though the study did not specifically look at impacts associated with fast charging [12].

The ability of the power grid to support XFC is a key area for consideration. The chief concern being that the addition of multiple charging stations and the associated overall power demand will increase stress to localized portions of the grid that have aging infrastructure. As an example, an XFC station with multiple, simultaneous charging events at a single location could result in power levels well over 1 MW. At these levels, the power demands surpass most buildings including large hotels and medium office buildings across the country [13].

Early studies of fast charging have shown that grid harmonics and voltage stability can both be impacted even at levels near 50 kW [10] [11]. These impacts coupled with high power demands highlights the need to develop control schemes that provide sufficient localized control. Examples to minimize the power quality and delivery impacts include the ability to effectively manage non-abrupt initiation and discontinuation of the charging protocol. Additionally, implementing smoothed ramping up and down and coordination between different charge equipment at the same XFC station may be needed to minimize non-ideal grid behavior.

Power quality is not the only issue that needs to be addressed at the utility scale. In addition to voltage and harmonic issues that could arise, there are also key issues that need to be addressed associated with both siting and the appropriate power feed to an XFC location. While at the base level, many of the specific XFC station needs will be location specific, there are a few commonalities that will arise. These include the need to have an adequate distribution feeder and the inclusion of an appropriately sized transformer. For XFC operation, this will likely entail the use of a pad mounted transformer such as a 2500 kVA transformer. With respect to the distribution feed, an XFC station would typically require an underground service and an associated switch cabinet, as is common for many commercial and light industrial locations with public access. Lastly, each station will need to follow the established codes for the specific location as well as for other governing bodies such as the NFPA and the Americans with Disability Act (ADA) requirements.

Coordination of an XFC network will also need to balance the needs of location specific charging stations with implementation across a broad geographic area, as their power surge has enough magnitude to propagate through the distribution and transmission network [14] [15] [16]. To alleviate propagation impacts, a proper system protection design needs to be implemented. This will likely require direct interaction with multiple public utilities and coordination with multiple PUCs. Across the United States, individual PUCs have different requirements for the sale of electricity and on overall cost structure. Additionally, there are other AHJs which impact the siting and requirements needed for the permitting and registration of charging infrastructure. The broad variability across the country currently stands as a possible impediment to widespread implementation of XFC infrastructure. A key to addressing this possible issue is a broad strategy to involve stakeholders from across the country to look at more uniformity as it concerns XFC infrastructure.

2.2.1.2. Demand charges and management

The cost of providing electricity for an EVSE at high power will be a crucial factor in the success of XFC. The components of delivered electricity cost broadly include electricity generation, transmission, and distribution. Utilities often use demand charges, which are based on peak power usage, as a tool to accommodate the delivery of electricity to customers during high demand periods. As such, demand charges are typically used for large electricity users that have high variability to provide compensation for the additional hardware and capacity that is needed to provide periodic high rates of power to the customer. This can require the installation or upgrading of distribution lines, transformers, and other equipment, and increased operation and maintenance costs.

XFC is expected to be intermittent during its initial implementation and even after initial implementation some rural stations that are part of corridors may see low utilization. Distribution equipment for irregular loads is usually oversized relative to that for more continual loads to mitigate the effects of intermittency. The costs associated with distribution network capacity upgrades must be recovered by the utility. Often, when utilities install a new service such as an XFC station, a connection fee is charged that covers a portion of the cost of the upgrade. The remainder of the cost is recovered through an energy charge (per kWh delivered), and/or a combined energy and demand charge that is calculated based on the peak kW delivered. Each utility has a differing rate structure for commercial users, some with proportionally high energy costs and others with high demand charges. For example, demand charges can range from $2/kW in Seattle to $8/kW in New York and more than $30/kW in Hawaii [17].

The impact of demand charges for fast charging is highly dependent on station utilization. When utilization is low, the energy provided is low, and the demand charge per kWh delivered is high. For EVSEs with low utilization providing high power charging, such as some DCFC locations from the EV Project, demand charges can account for a significant portion of the cost of operating the station and can make these stations unprofitable [17]. With XFC, the peak power demands will be significantly higher, so understanding how to mitigate high demand charges will be very important.

With higher utilization, an EVSE's profitability becomes less dependent on demand charges as shown below. If XFC stations are sited in locations with a sufficient BEV population that uses the stations frequently, high utilization will not be an issue. However, in corridors and other sites that have lower utilization, demand charges will be a larger issue. Therefore, an analysis of what XFC station utilization is needed to make a station viable would be very useful. The development of sample rate structures for XFC stations could be useful for utility outreach. For example, a high energy charge and low demand charge for low utilization (early stations) and a low energy charge and high demand charge for a high utilization (mature stations).

Demand side management (DSM) has been used to mitigate impacts of peaky loads, through the control, including curtailment, of power demanded during times when the grid is operating near peak capacity. A key feature of DSM is that high power loads are typically impacted at lower rates than lower power loads [23]. As mentioned in section 2.2.1.1, an XFC station is likely to have instantaneous power demands, which are on the order or greater than what is seen for many mid-sized buildings in the United States. This level of power would suggest that XFC may not be an optimal choice for DSM and is counter to many discussions suggesting that BEVs could be a prime use case for DSM [24] [25]. Where XFC differs from standard DSM for BEVs is that for its optimal utilization and to ensure consumer confidence there needs to be ready access to full power. Curtailing power to XFC stations, even briefly may decrease utilization of XFC stations by BEV drivers.

Key technological possibilities to reduce the impact of demand charges include on-site renewables that could minimize the total load needed from a utility and stationary energy storage that could be used to supplement grid demand and as a result smooth the use of energy. A side benefit of implementing demand response capable XFC on a distribution feeder, is that it would provide means to absorb excess renewable penetration either through charging events or when combined with stationary energy which could directly supplement charging needs. Both means could help mitigate negative ancillary effects of renewable variability and uncertainty, improving grid reliability and maximizing the renewable generation and revenue [18].

2.2.1.3 Integration of Renewable Generation and Stationary Energy Storage

Use of stationary storage to effectively minimize or remove demand charges requires that the storage be capable of operating during the high power portions of charging events and also be able to remain in operation for extended periods of time. Recent work has shown that there is some ability to use energy storage options to minimize the full impact of power demand during a fast charging event [19]. During high use times, multiple XFC events may occur either simultaneously at a single location or back-to-back at the same location. At an example station that has six charging ports, the power supplied by the energy storage could be greater than 1 MW and the overall capacity may exceed 500 kWh. An effective energy storage solution would need to be able to buffer both the power and energy demands of such a station. The other key consideration for stationary energy storage is that it would need to be charged at a sufficiently fast rate or be sufficiently oversized for a specific location to facilitate many events in a short time frame such as during as a rush hour period. The inability to meet the demands of all XFC events would lead to increased demand charges and partially negate the benefits of the stationary energy storage.

The side benefit of stationary energy storage is that during low use times it may be possible to use the storage to provide ancillary services for grid operation. However, the extent of benefit would be very much dependent on location and services needed, as significant peak load shifting would not be feasible due to the need to retain availability for possible XFC events. Other ancillary services such as frequency regulation may be feasible. Storage systems (both Li-ion and flow batteries) which could meet these demands are already being integrated into other grid and microgrid settings often in conjunction with renewable energy generation assets. However, there are challenges in providing ancillary grid services. Two that are distinctly apparent are market size and market risk. With respect to size, the demand aggregator needs to be able to provide at least some minimum demand to the ancillary services market, but the market size is limited, so the market can saturate quickly. Market risk is also important, as prices for ancillary services are volatile. Thus, the key to incorporation of storage with XFC is the combination of appropriate control schemes, and economic considerations for installation, maintenance and replacement due to performance fade of the installed storage or changes in use conditions for the XFC location.

Analysis of when DCFC are used during the work week has found that for current installations the highest use rates were closely aligned with the evening commute between the hours of 5 and 7 pm. [20]. The same study found very little use between midnight and 6 am. This data, while dating to 2013, suggests that it is probable that the enhanced implementation of other fast charging options such as XFC would have high use rates during the same time period. With such a use scenario, it is feasible that the integration of localized renewable generation, especially solar, at the XFC station could curb demand during the day with an additional buffer from stationary energy storage. The storage could then be charged from either excess renewable energy during the day or from the grid during off-peak nighttime hours.

However, other issues could arise for the inclusion of XFC in areas that have high renewable generation, but which lack sufficient storage. A key example of this is California, which has mandates for high penetration of renewable power generation. California ISO has projected there will be a need for sufficient ramping of generation during the evening hours, especially in the spring and fall to account for renewables going off-line and the increase in power consumption as residents go home at the end of the work day [21]. This projection, sometimes referred to as the duck curve, includes the assumption that more renewables are added to the system, but that overall energy use does not increase, shows the need for ramping of close to 13,000 MW over a three hour period. What it does not take into account is that if transportation becomes more electrified there will be a net increase in grid energy demand. If patterns for XFC use during the work week mirrors the use of early adopters of DC fast chargers [20], the increased demand during and just after the evening commute from 5-8 pm could exacerbate issues associated with ramped generation or require additional storage capability.

As an example in 2015 there were just over 24 million registered light duty vehicles in California [22]. If adoption of XFC-capable BEVs advances to encompass 10% of the vehicles (2.4 million vehicles) and if 5% of those vehicles (120,000) fast charge during the 5-8 pm rush hour peak period [20], between 6500 and 7700 MWh of additional total generation would be needed if each charging event replenished close to 200 miles of driving range (57 kWh). The variation being due to efficiencies in chargers and variation in the energy needed per mile of driving distance replaced. Regardless of extent of renewable integration into the grid, this level of ramping needs to be accounted for in areas where it is foreseen that high levels of adoption of XFC capable vehicles are possible.

2.2.2. Charging Stations

The implications of XFC on infrastructure extends beyond just grid and utility operation. The ability to effectively provide XFC for BEVs will require the implementation of charging stations at specific locations which are capable of providing the power and also being readily accessible to a populace with a higher adoption of BEVs. The design of these charging stations needs to take into account a host of different issues as shown in Figure 2B. The stations also need to be part of corridor planning, which takes into account the human psychological perspective to allow consumers to feel unburdened by the distance between XFC stations. Satisfying this condition may require some overbuilding of infrastructure or better education and distribution of pertinent information such as range to consumers [26].

Regional variation in acceptance may also be a key consideration during the planning process. This combined corridor optimization will require advanced understanding of BEV use patterns which are expected to change as BEV adoption rates increase, as BEV range increases and as BEVs become more viable for those that do not have access to home charging. In parallel with understanding BEV use, the corridor planning effort must be cognizant of grid issues such as anticipated changes in generation mix and aging substations, distribution and transmission lines. Much like the integration of renewables and localized stationary energy storage, the other area that must be part of corridor planning efforts is understanding how XFC EVSEs impact the overall functioning of the grid and if there are any issues which could emerge due to high use of XFC infrastructure.

The flow of vehicles presents a possible challenge that does not exist for refueling ICEVs. The general layout of a XFC station would entail multiple charging ports that would be situated to optimize flow of vehicles. For XFC, flow pattern is crucial due to the less consistent amount of time needed for charging when compared to ICEVs. Much like refueling stations for ICEVs, a key area of interest is how to get new, low charge BEVs into open ports as they become accessible. This is especially pertinent as the likely scenario, based on prior data obtained from the use of DCFC, is that most cars will be arriving with a state-of-charge below 40% [27]. Current BEVs have charge ports in more disparate locations (i.e. the side versus the back of the vehicle), which does not readily lead to the easy movement of vehicles into and out of an XFC station. Facilitation of XFC station throughput could be aided by standardization of the location of vehicle charge ports across manufacturers or the development of longer cables. However, as discussed below in section 2.2.3.1, cable weight could become a key concern.

2.2.3. Electric Vehicle Supply Equipment (EVSE)

2.2.3.1. EVSE technical issues (cable, voltage, connector)

Figure 2C defines the key issues associated with the implementation of EVSE for XFC purposes. Among the most significant challenges are those associated with the type of charger and its compatibility with existing BEVs. These issues are much less focused on development of new technologies, but more so on the joint understanding of how technologies can be used and how codes and standards for multiple organizations can be unified. Of particular impact is the unification of codes and standards put out by the Society of Automotive Engineers (SAE), and the National Electrical Code (NEC) put out by the NFPA, while still meeting the needs of the Occupational Safety and Health Administration (OSHA).

An example of the interplay between the different governing bodies can be found in comparing what type of cabling limits arise when following both the NEC cable sizing requirements and the OSHA limits for lifting (Figure 3). A 50 kW DCFC cable is the closest example that currently exists that can be compared to a future XFC cable. The DCFC cable is typically 12 feet long and compromised of 2 AWG (American Wire Gauge) conductors for the DC charging current up to 125 A. A 12 foot long CHAdeMO cable mass is 23 pounds including the connector. Since most cabling systems suspend half of the cable, the driver/operator only has to lift half of the mass since the other half is supported by the DCFC.

For XFC systems without a significantly higher voltage than what is currently used for DCFC, the current requirement of the cabling increases to nearly 900 A. This requires wire gauge sizing that weighs over 10 pounds per foot. With a higher battery voltage, the current requirement significantly decreases but cable wire gauge size is still a concern. The issue of using standard cabling is shown in Figure 3. The figure shows how with increasing power levels there is a distinct increase in cabling weight. At a battery voltage of 800V, the current requirement is over 400 A, which requires MCM 350 wire gauge that weighs over 8 pounds per foot, where MCM is an abbreviation for a thousand circular mils. Again assuming a cable management system that only requires the driver or XFC station operator to move 6 feet of cable, the resulting mass is 57 pounds. This cable mass exceeds the OHSA lifting limit for a single person. Indeed for both 400 and 800V systems the cabling exceeds the OSHA limit well below 400 kW minimum charger powered needed for the defined XFC charge. Only when the voltage level increases to 1000V does the cable weight remain near the 50 pound OSHA limit.

The use of liquid cooling could significantly reduce the overall cable mass and allow the average consumer the ability to charge using an XFC EVSE. However, there is currently no set agreement on how to accommodate liquid cooled cables within the National Electric Code (NEC). Another option would be the use of robotic or automated charging stations. A third option to not have heavy cables for conductive XFC is the use of high power wireless charging. To date high power wireless charging has been demonstrated at 50 kW with plans for expansion to 200 kW and beyond for buses [28]. To enable wireless charging either large single coils or multiple coils are paired together (side by side in parallel) with the size of the coil dictating the overall power capability. One current issue is that with existing technology the size of the coils needed for wireless XFC would be greater than the underside of a typical sedan. Additionally there are potential safety concerns with respect to electromagnetic field emissions surrounding such a high power wireless charging system. Thus, while a possibility, the overall feasibility of using high power wireless charging for light duty vehicles is questionable.

The need for greater uniformity in the location of charging ports to facilitate XFC has been put forth in the section 2.2.2 relating to charging stations. With respect to the EVSE a similar enhancement in uniformity to a standard, high power connector would significantly improve XFC planning. Currently with three primary DC fast charging connectors in the United States (SAE J1772 CCS, CHAdeMO and Tesla) harnessing a single station for quick XFC would be problematic. Efforts to unite on a single connector for XFC purposes is something which will require direct codes and standards involvement on the part of industry (both vehicle and EVSE manufacturers) and independent specialists such as those located within the Department of Energy national laboratory system. This is similar to what occurred for other EVSE codes and standards efforts, such as those associated with SAE J1772 and SAE J2954.

2.2.3.2. EVSE installation and equipment costs

The cost of XFC installation and equipment is an important factor in understanding the business case of this technology. Current DCFC installation costs vary significantly and often depend on how close the EVSE is to existing power infrastructure. Analysis from the Recovery Act EV Project, found that 111 DCFC installations ranged from $8,500 to over $50,000, with a median of $22,600 [29]. The addition of new electrical service was the largest cost driver. For example, if the DCFC location did not have adequate service nearby, a transformer, switches, and long conduits would need to be installed and would increase costs. The cost to purchase and install a transformer is around $18,000 [30]. The surface type where wiring and conduit were installed was the second largest cost driver. For example, if a significant amount of concrete or asphalt needed to be removed and replaced a substantial increase in installation cost would result. The least costly installations were at retail shopping centers that had adequate electric service and that required either short, hand-shoveled underground or surface-mounted conduit service.

As XFC will require locations with excellent electrical service, the cost of installations could be more expensive than those for DCFC. Understanding the installation and interconnection cost of XFC at an “optimal” versus “non-optimal” site is necessary for planning XFC locations. Francfort performed a rough order of magnitude analysis of the costs of a charging complex with six EVSEs, comparing DCFC (at 50 kW) and XFC EVSEs at rural and urban corridor locations.

The installation cost estimate per XFC EVSE ranged from $40,300 to $42,000 or about $7,300 to $9,400 more than the cost per DCFC [29].

Currently DCFC systems are available that provide 145 kW charging (Tesla), with plans in the near-future to deploy 225 kW systems (Porsche). Dual-port DCFC hardware costs for chargers rated at 50-60 kW are estimated to be between $20,000 and $36,000. Francfort et al. estimated the equipment cost per XFC EVSE to be $245,000 as compared to the $30,000 DCFC EVSE [29]. While initial experience by OEMs developing these high power systems found that the equipment costs may be significantly higher, the expectation is that they will be similar in cost to current systems once they are beyond the prototype development phase.

A distinct difference between lower power DCFC and XFC equipment is the cabling that is necessary for higher power. As charge power increases the current, the conductor size and weight increases as discussed above in 2.2.3.1. In order to reduce the size of the charging cable, cooling is likely required. The addition of liquid cooling increases the complexity of an EVSE due to the need for pumps and a reservoir of coolant. Cables guided by robotics could also be used instead of vehicle operators but again this would increase the overall complexity of the EVSE. Both routes to deal with increased cable weight are likely to increase the equipment and maintenance costs.

2.2.3.3. Subscription options

XFC stations will need to be installed in sufficient numbers and in appropriate locations to influence adoption of BEVs that are capable of XFC. This requires investment in charging infrastructure that may not be fully utilized until the BEV market grows, making the investment risky. Fleets owners of centrally recharged XFC BEVs might be able to support the fleet with a predictable and affordable number of XFC stations, with locations known before installation. However, the numbers and locations of public XFC stations needed to promote adoption of XFC BEVs will be difficult to predict. Public XFC infrastructure may require a phased deployment in conjunction with an XFC BEV adoption campaign. First, by deploying XFC chargers in locations to support early adoption of XFC BEVs, then expanding to additional locations as adoption increases. Public EVSE network providers and operators will need to consider different business models and rate structures. Several models exist, including: per kWh, per minute, and subscription.

It is difficult for a public charging station to realize sufficient revenue from electricity sales (per kWh charging), as has been documented by several studies [31] [32] [33]. Some networks charge on a time-basis (per minute) or charge a subscription fee, for access to chargers in their network, or a combination. Charging on a time-basis is often done for Level 1 and 2 EVSEs in locations where parking is at a premium and turnover for charging access is desired. A subscription fee compensates the EVSE network provider for making the EVSE available, independent of the utilization, and subscribers realize the value of the availability of EVSE stations “just in case”, even if they charge mostly at home or elsewhere.

2.2.4. Cyber and physical security

One area that crosses all three levels of infrastructure needs for XFC is the combination of physical and cyber security. Due to the high rate of energy transfer needed for XFC there has to be private and secure communication between the vehicle and the EVSE. Likewise, communication between the grid and the charging station is expected. This tiered communication presents the possibility that significant cyber security issues could arise with an expansive XFC network. The risk is that breaches in security could impact not just individual vehicles or charging stations, but could cascade to impact broad swaths of transportation infrastructure or the grid.

It is important to continuously assess the resiliency of a physical system such as an XFC station by using scientifically sound techniques. The impact of maloperation of XFC on the power systems needs to be assessed and control actions to counter impact should be designed in advance. The use of different techniques including real-time simulation can identify unfavorable operating conditions that result from cyber and cyber-physical attacks on physical systems. With the use of different simulation and actual device assessments, proactive insights can be leveraged to prevent malicious operating conditions from occurring, or minimize damages if they do happen.

2.3. Battery and vehicle costs and considerations

Battery costs are a critical driver of BEV price and ultimately the total cost of ownership of a vehicle. Li-ion batteries for BEVs have seen significant reductions in costs in the past 10 years, and recent news suggests that battery pack costs are now below \$200 kWh^{-1} [34]. While Tesla battery packs are capable of charging to 120 kW, the cost implications for XFC-capable batteries are not clear [35]. XFC could impact factors such as battery lifetime, chemistry adopted, cell design, and thermal management and these issues require analysis [1, 2]. Fast charging can have implications on battery degradation, so understanding the cycle life implications of BEVs using

XFC at different frequencies is needed. For drivers who only use XFC occasionally this may not be an issue, but for multi-unit dwellers or commercial fleets who use them frequently performance degradation could be a concern.

Battery chemistry and cell design changes made to improve battery charging performance and lifetime, will impact production costs [1]. If XFC-capable BEVs are warrantied as are current BEVs (battery life warrantied for 8 years or 100,000 miles, whichever occurs first, [[36]), and the cost to automakers of warranty battery repairs and replacements are included in the BEV price, then reduced battery lifetimes would impact the vehicle price.

While the largest impact of XFC on vehicle costs is likely to be battery costs, other vehicle costs for the implementation of XFC may include high voltage power electronics, cabling and connectors, and improved thermal management assessment [2] [3]. It is likely that XFC-capable BEVs would not have different vehicle energy efficiency from non-XFC-capable BEVs, therefore the energy costs will be driven more by the cost of electricity per kWh than the amount of electricity consumed per mile, assuming losses in the XFC EVSE are not much higher than losses in DCFC EVSE.

Since vehicle costs, amortized per mile depend on the distance driven, the enhanced usability of BEVs provided by XFC may enable users to drive BEV greater distance, making BEVs more economical than conventional vehicles on a per-mile basis if the electricity cost per mile is less than that of gasoline. XFC-capable BEVs may be economically advantageous for users who drive many miles per year. However, uncertainty in battery lifetimes due to potential battery degradation might reduce resale value. Some BEVs are reported to depreciate faster than comparable conventional vehicles, but high-performance/luxury BEVs appear to retain value well [37] [38]. It is unknown how XFC-BEVs would depreciate, but if introduced in the luxury-performance segment (and if batteries do not degrade), XFC-BEVs may hold their value well.

2.4. Value of time

Travel demand is typically generated from the activities at the destinations of trips. Travel time has a negative utility; it is something private and commercial users have a willingness to pay to have less of. The value-of-travel-time-savings (VTTS) is often used in government cost-benefit analyses of regulatory actions and investments in transportation to make sure resources are used appropriately. The VTTS varies depending on multiple factors including the individual traveling and the type of travel. The U.S. Department of Transportation (DOT) has analyzed this topic and provided guidance on how to use VTTS in economic analyses [39]. However, analysis of VTTS for both consumer and fleet BEV drivers would help determine the economic viability of XFC.

Research has typically found VTTS for personal travel to be lower than the hourly earning rate. For local personal travel, the DOT estimated the VTTS at 50 percent of hourly median household income [39]. In 2012, the median hourly income was $24.50 per hour, resulting in a local VTTS of $12.25. The DOT examines intercity personal travel separately as estimates of VTTS rises with distance of a trip. For intercity personal travel, the DOT estimated the VTTS at 70 percent of hourly median household income, which was $17.20 per hour in 2012 [39]. An analysis of the

VTTS for various consumer segments would help determine the cost limits that XFC would need to meet to provide consumer value.

There is wide agreement that the VTTS for business travel should equal the gross hourly cost of employment, including payroll taxes and fringe benefits. For local and intercity business travel and commercial vehicle operators, the DOT assumed the VTTS to be equal to a nationwide median gross compensation, defined as the sum of the median hourly wage and an estimate of hourly benefits. Their estimate for 2012 was $24.10 [39]. The values will vary for different commercial uses such as taxi, ride-share, and bus. Therefore, analysis of VTTS for these segments is needed to understand XFC potential in commercial applications.

2.5 Social Benefits

To the extent that XFC can increase adoption of BEVs, benefits to society can be realized through increased energy security. However, since effects of oil dependence and emissions are not explicitly captured in vehicle or fuel purchases, they are externalities, therefore consumers tend to consume and emit more that if vehicle and fuel transactions included the costs of externalities [39]. These externalities are market inefficiencies that can limit the benefits that BEVs can potentially provide. Federal, state, and local governments and other public entities may choose to promote BEVs in order to realize some of these benefits [17]. One way to promote BEV adoption would be to support deployment of XFC chargers in order to increase adoption of BEVs by those who cannot conveniently charge vehicles at home or at work. Support can take various forms, such as subsidies, incentives to EVSE network providers, education and outreach, coordination between authorities having jurisdiction over EVSE installation and operation to help reduce regulatory and permitting barriers.

2.6 Economic analysis

2.6.1 TCO analysis

Using the cost data discussed in earlier sections, we analyzed the total cost of ownership of an average passenger car with 4 different powertrain/charging options: 1) gasoline ICEV 2) gasoline HEV 3) BEV solely using DCFC and 4) BEV solely using XFC. The use of a single charging regime (100% use of DCFC or XFC) in this calculation is intended to define a limiting case that highlights the differences in each technology. This may not be a realistic assumption for many BEV drivers, though may represent a case for those who do not have the ability to charge at home or work, such as multi-unit dwellers. Table 1 summarizes key inputs for this analysis.

Results in Figure 4 show that the incremental price and resulting depreciation of both BEVs account for a significant portion of the TCO. Typically, a BEV will have significantly lower fuel costs due to the low price of electricity. In this scenario, the BEV only uses either DCFC or XFC and the electricity price paid in each scenario includes the cost amortization of the EVSE equipment, installation, maintenance, and demand charges based on the assumed station utilization. The BEV-DCFC has $6,000 lower lifetime fuel costs than the ICEV and $1,000 lower fuel costs than the HEV. The XFC-BEV has higher fuel costs ($3,000) than the ICEV due to the high cost of the XFC EVSE equipment, maintenance, and demand charges. Both the BEVs have lower maintenance and repair costs than the ICEV, as no battery replacement is assumed. When comparing the two BEV scenarios, the value of time travel savings becomes a significant factor in the TCO. The XFC-BEV would spend about a 900 hours less charging than the BEV-DCFC, accounting for about $23,000 in VTTS. This analysis shows that both XFC vehicle and fuel costs will have to decrease in order for it to show a strong economic benefit versus ICEVs or HEVs.

Another important takeaway of a TCO analysis is to look at how sensitive results are to changes in assumptions. Table 2 has the sensitivity case assumptions. When comparing the XFC-BEV to the ICEV (Figure 5), the station utilization, electricity demand charge, gasoline price, BEV incremental cost, base electricity price, and EVSE hardware cost all can significantly impact results.

2.6.2 EVSE utilization and demand charges

With the utilization (12 sessions day^{-1}) assumed in the default case, the $8 kW^{-1} demand charge accounts for 38% of the estimated total electricity cost. The total electricity cost that the driver would pay ($0.34 kWh^{-1} in base case) includes the base electricity price from the utility and the breakeven cost to amortize the EVSE hardware, installation, operation (includes demand charges) and maintenance costs over an assumed 15 year EVSE lifetime and kWh dispensed (profit not included). If the station is used 6 sessions day^{-1} with the same $8 kW^{-1} demand charge, the total electricity cost jumps to $0.58 kWh^{-1}, with the demand charge accounting for 45% of the cost. As seen in this example, the demand charge can be a significant portion of the price to charge an XFC-BEV. If station utilization is low, fixed costs such as demand charges and hardware equipment cost and maintenance becomes an increasingly important cost factor (Figure 6). Figure 6 shows the breakeven charging cost both in $ kWh^{-1} and $ eGallon^{-1}, which takes into account the relative efficiency benefit (3.5 times) of the XFC-BEV versus its gasoline counterpart.

2.6.3 Charging station renewable generation and stationary energy storage

Francfort et al. examined the equipment, installation, and operating costs of a six EVSE XFC complex with and without the use of photovoltaics (PV) and stationary energy storage [29]. Their estimates were based on the PV providing 25% of the energy supply and the PV and energy storage reducing maximum grid power demand by 85%. These systems were sized on assumed station utilization patterns (rural locations had longer charge times but were used less frequently than urban locations). The values in Tables 1 and 2 are in close alignment with those generated by Francfort et al. but are scaled to the single XFC port level [29].

The PV equipment was assumed to cost \$200 kW^{-1}, with per EVSE cost ranging from \$3,000 to \$4,000. The stationary energy storage system (ESS) was assumed to cost \$400 kWh^{-1}, with the per EVSE cost ranging from \$21,000 to \$59,000. The total equipment and installation cost of the charging complex with PV and ESS ranged from \$1.4 million to \$1.7 million. Due primarily to the assumed higher cost of the EVSEs in the scenario without PV and ESS, the estimated total equipment and installation cost without PV and ESS was \$56,000 to \$300,000 higher. In addition, the annual operating savings due to reduce demand charges for the charging station with PV and ESS ranged from \$130,000 to \$175,000. While this area needs further analysis, these systems show the potential for cost savings with the incorporation of energy storage or distributed renewable energy generation integration.

3 R&D, Industry, and Education Considerations

To address uncertainties, challenges, and implications facing the deployment of XFC, a number of questions need to be researched. In addition to R&D questions, resolution of issues facing EVSE network providers, operators, utilities, and users should be addressed, requiring coordination between various actors, standardization of technologies and practices, and education of users and other interested parties.

3.1 Near-term R&D

In the near-term, research is needed to support effective coordination of corridor planning. Understanding where XFC stations need to be sited to serve demand by BEV drivers and where the appropriate grid resources exist to initially serve the greatest number of consumers are two important research areas. Within these issues, there are a number of specific questions and research needs.

To better understand potential adoption levels of XFC and XFC-BEVs, market research is needed for several potential market segments, including both private vehicle owners and commercial and government fleet managers. The market for private vehicles is heterogeneous with individual owners having a different value of travel time, need for range, preferences for other vehicle features, and willingness to pay for XFC. Commercial and government fleets, including drivers of transportation network companies such as Uber or Lyft, are diverse with different requirements for the times and distance that vehicle are operated, the value of (or lost revenue from) time spent charging, and type of vehicle required. Therefore, many possible use cases need to be considered to assess the utility of XFC to potential user segments. Market research should consider the potential influence of incentives and other policies to promote BEV adoption, since automakers and government agencies may choose to provide funding for XFC stations to increase BEV sales.

Adoption and use patterns will determine charging demand at different locations and times of day. Estimating future demand and potential utilization of XFC stations will be key to assessing the economic viability of these stations and their impacts on the grid. The economics of stations depend not only on installation and operation costs but also on utilization. In the early stages of XFC deployment, even well-sited stations may not be heavily utilized, and revenues from providing charging will very likely be insufficient to defray these costs. Moreover, the costs and revenue for a given station will vary widely depending on site-specific characteristics. Multiple case studies will be needed to assess the range of equipment, installation, and operation costs under different probable utilization patterns. Key to these case studies will be analysis of various approaches to manage the cost of supplying power to the station, particularly the demand charges when station utilization is low. Examples described above represent several of possible approaches to manage high-power, intermittent demand of an XFC station. Further research is needed to better understand the economic tradeoffs and operational benefits of on-site storage, integration with distributed generation, and advanced technologies and management practices for operating distribution networks.

In addition to the above research, more materials research and equipment design engineering are needed. Technological improvements could include advanced materials with better thermal and electrical properties to reduce and manage thermal loads in the EVSE and its cable.

3.2 Long-term R&D

In the long-term, research will be needed to address challenges germane to widespread XFC deployment and possible challenges arising from changes in travel patterns and vehicle ownership. Widespread, heavy use of XFC in combination with automated and connected vehicles, many of which may be shared-used vehicles may result in different demand patterns than those seen in early deployment. Future technology may enable XFC with little or no actions by drivers through automated and even wireless EVSE.

3.3 Industry needs

Beyond R&D, other actions will be needed to implement XFC. Across the country, there are a multitude of different authorities having jurisdiction over permitting, siting, and regulation of charging stations. Coordination and harmonization of permitting, siting and regulatory requirements would simplify XFC planning and deployment. Unifying and harmonizing codes and standards would also be beneficial, including items such as applicability of liquid cooled cables, connector design, and cabling limitations. Industry and AHJ engagement in standardization organizations such as SAE, NFPA, and others will be needed.

3.4 Education needs

Successful deployment of XFC and adoption of XFC-BEVs will require education of both consumers and other stakeholders on the merits of vehicle electrification. The U.S. Department of Energy, through its Clean Cities and Workplace Charging programs has engaged in a range of education and outreach efforts to promote BEV adoption, as are a number of other organizations, such as state agencies, non-governmental organizations, not to mention automakers marketing their BEVs [41]. As XFC challenges are addressed through research and other activities described above, consumers and others need to be educated on XFC and BEVs so they can make informed decisions. Education efforts will need to be tailored to the particular user segment and stakeholder group.

4 Conclusions

Extreme fast charging consisting of DCFC systems capable of power up to 400 kW, would allow BEVs to recharge about 200 miles of driving distance in 10 minutes. This brings BEV recharging much closer to the experience that consumers are accustomed to with ICEVs. While this clearly offers greater utility to BEV drivers than slower charging systems, several important uncertainties need to be addressed before it is clear how these chargers and XFC-capable BEVs might be deployed, including:

- The cost of the charging equipment, installation and operation
- The cost of XFC-capable BEVs
- The future markets for XFC-capable BEVs by different users (commercial and private)
- Planning future XFC installations and networks, including siting and planning for future demand
- Viable business models for XFC stations under low and slowly increasing utilization; in particular, potential revenue streams for XFC network operators other than from selling electricity
- Management of the intermittent, high power demand by XFC stations, particularly when station utilization is low.

Addressing these uncertainties will require research and analysis. Important research needs include

- Development and analysis of scenarios of possible future deployments of XFC networks to better understand siting, taking into account existing grid resources and potential future XFC utilization. Such scenario analysis should consider how XFC will influence adoption of BEVs and the potential uses and business cases for XFC-BEVs under different market conditions and policies.
- New technology and operations practices to more effectively manage distribution grids with intermittent, high-power loads such as XFC stations with integration of stationary storage and distributed generation.
- Cyber and cyber-physical security of XFC infrastructure.

In addition to research, additional actions will be needed such as

- Increased coordination between multiple utilities, EVSE network operators, and AHJs over permitting, siting and regulation of charging stations.
- Increased standardization to ensure safety and to increase interoperability and backward compatibility.

Although deployment of XFC faces many issues, with sufficient progress in the above research areas and in battery technology, XFC could offer greater convenience and utility for BEV drivers, in particular private owners without access to charging at home, as well as those traveling along corridors and commercial BEV operators with a high value of time. With increased BEV adoption, there is the potential for decreasing petroleum use and decreasing emissions, with benefits of improved energy independence and reduced impacts to the environment.

Acronyms

PHEV	Plug-in hybrid electric vehicle
EV	Electric vehicle
BEV	Plug-in battery electric vehicle, includes both EVs and PHEVs
RD&D	Research, development and deployment
EVSE	Electric vehicle service equipment
ICEV	Internal combustion engine vehicle
DC	Direct current
DCFC	DC Fast Charging
AC	Alternating current
XFC	Extreme fast charging (between 150 and 400 kW)
NFPA	National Fire Protection Association
AHJ	Authorities having jurisdiction
PUC	Public utility commission
DSM	Demand side management
OEM	Original Equipment Manufacturer
TCO	Total Cost of Ownership
AWG	American Wire Gauge
CC-CV	Constant Current, Constant Voltage Charge Regime

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Figure Captions

Figure 1: Cost per mile of cash flow or payback of XFC BEVs issue tree

Figure 2: Grid (A), Charging station (B) and EVSE (C) issue trees for the implementation of XFC

Figure 3: Comparison of uncooled cabling for EVSE operating at 400, 800 or 1000V. Calculations a using different copper cables which meet the NEC ampacity ratings and use the current weight of a CHAdeMO connector.

Figure 4: Passenger vehicle 15 year total cost of ownership based on vehicle propulsion system configuration

Figure 5: Total cost of ownership of a XFC BEV compared with an ICEV.

Figure 6: Passenger vehicle 15 year total cost of ownership based on vehicle propulsion system configuration.

Table 1: Summary of key inputs for ICEV, HEV, and BEV TCO analysis

Table 2: Summary of sensitivity cases for TCO analysis

Figure 1: Cost per mile of cash flow or payback of XFC BEVs issue tree.

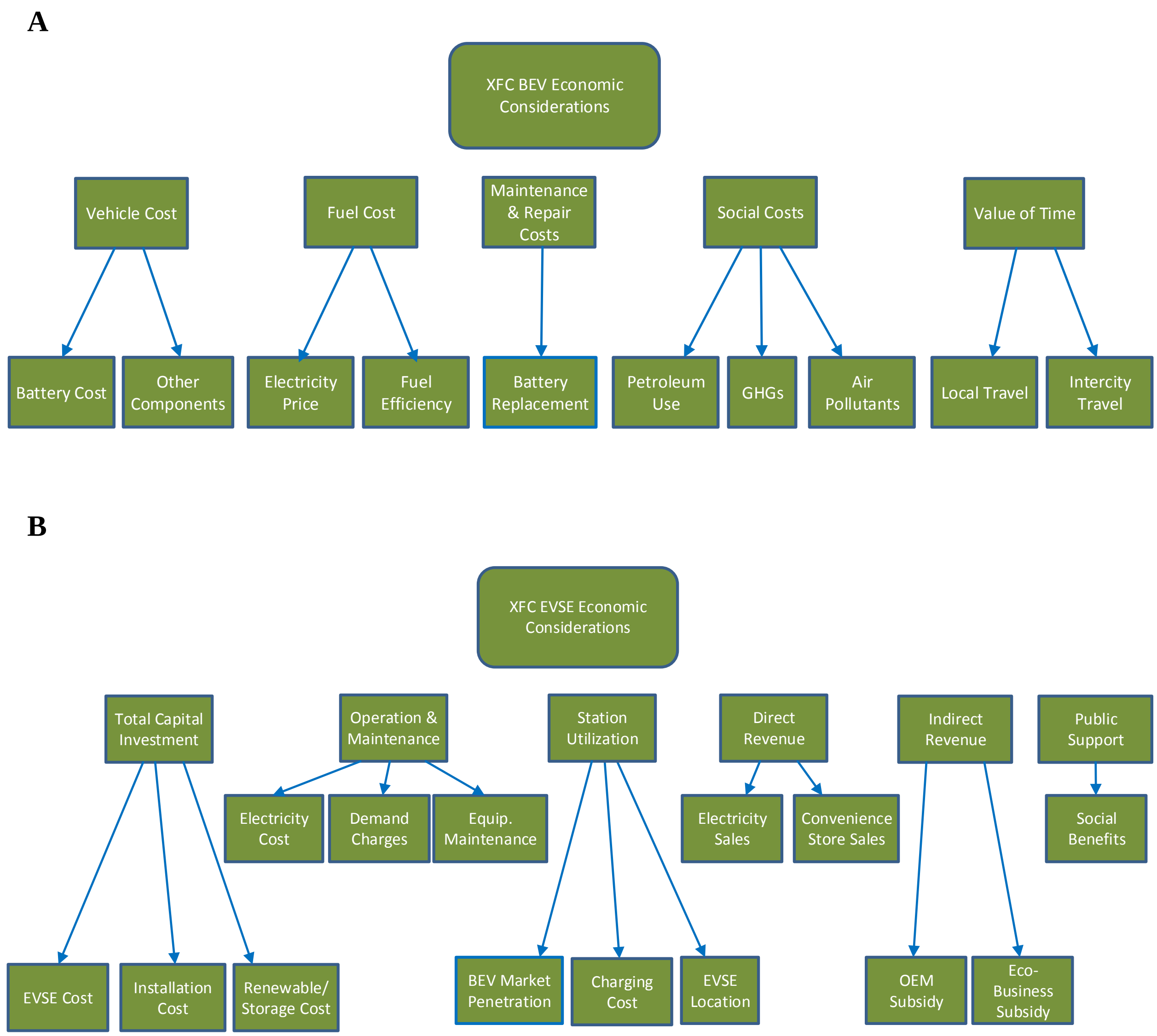

Figure 2: Grid (A), Charging station (B) and EVSE (C) issue trees for the implementation of XFC

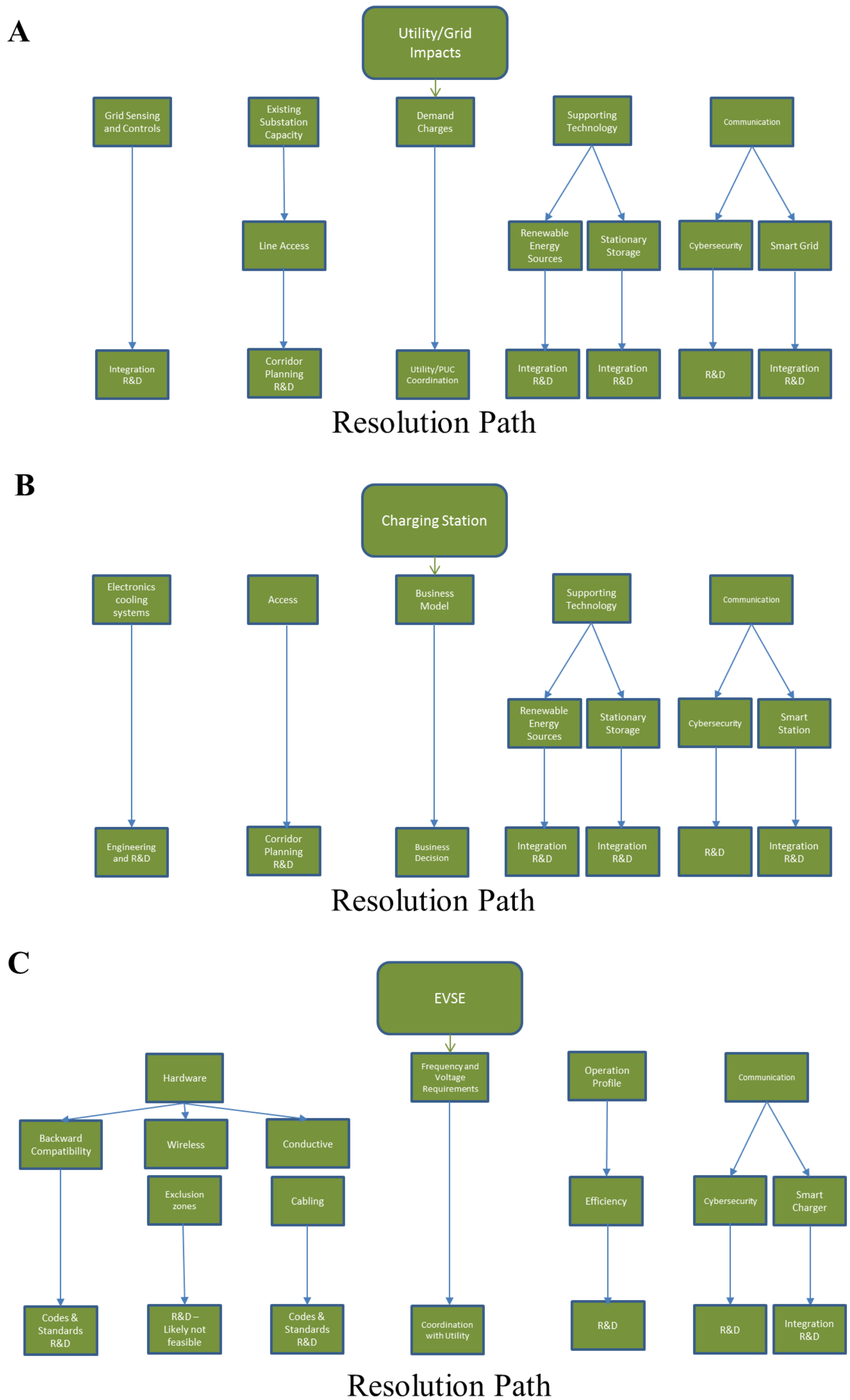

Figure 3: Comparison of uncooled cabling for EVSE operating at 400 or 800V. Calculations a using different copper cables which meet the National Electric Code (NEC) ampacity ratings and use the current weight of a CHAdeMO connector.

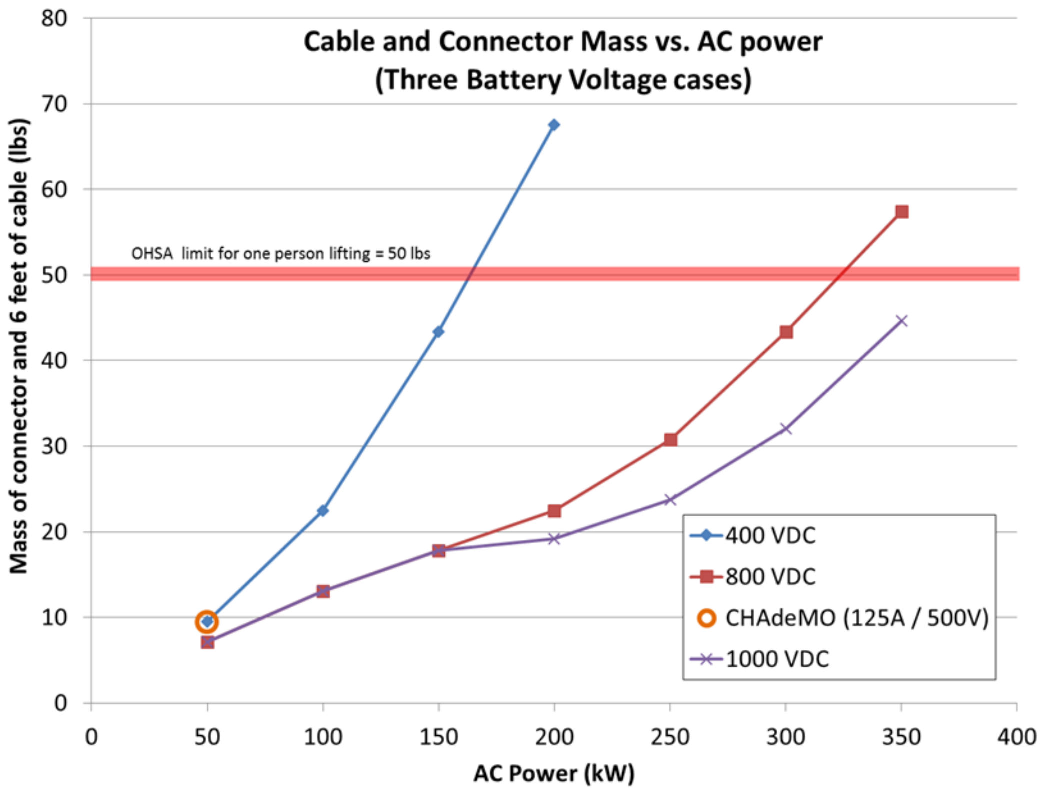

Figure 4: Passenger vehicle 15 year total cost of ownership based on vehicle propulsion system configuration

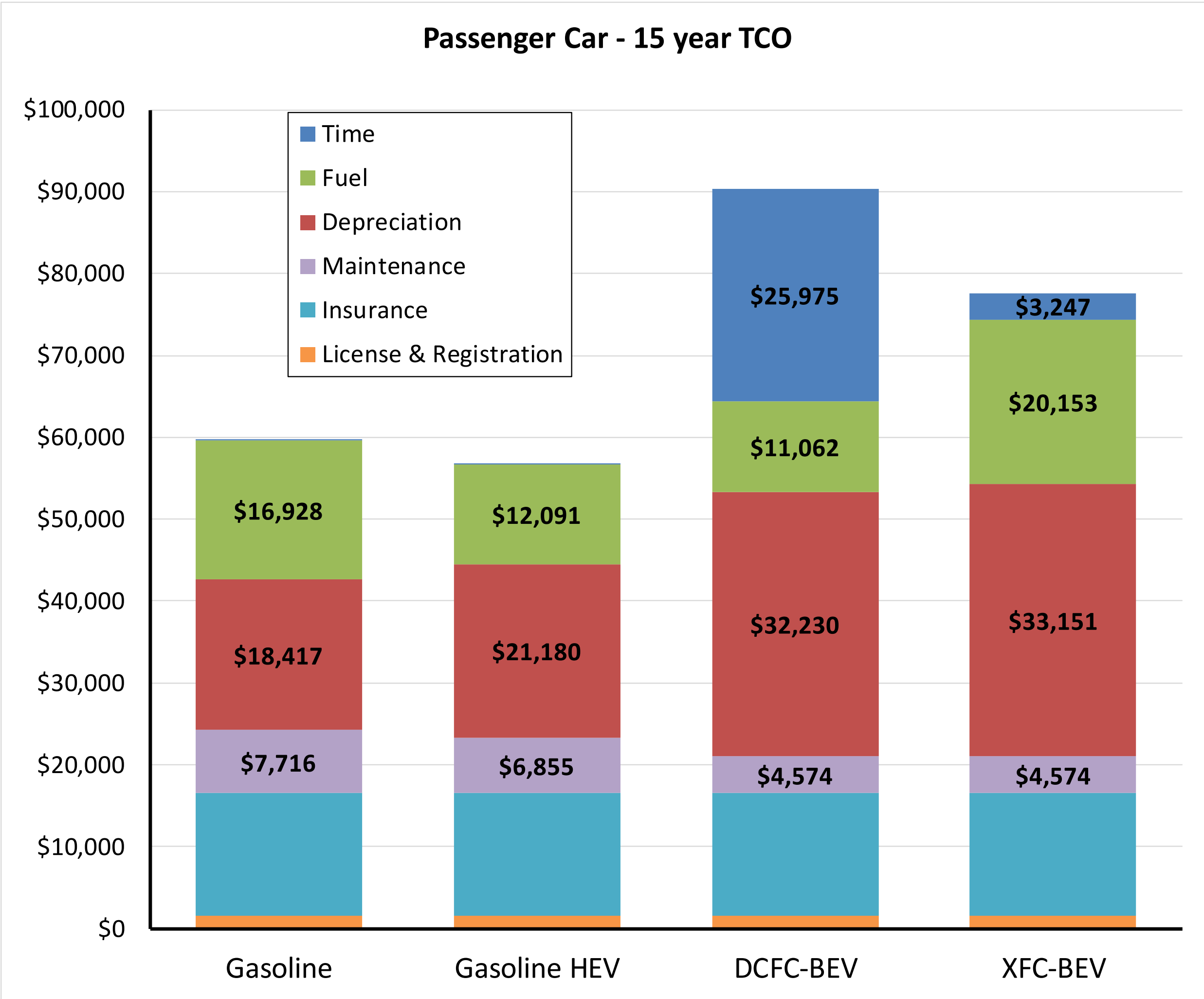

Figure 5: TCO Difference: XFC-BEV compared with an ICEV.

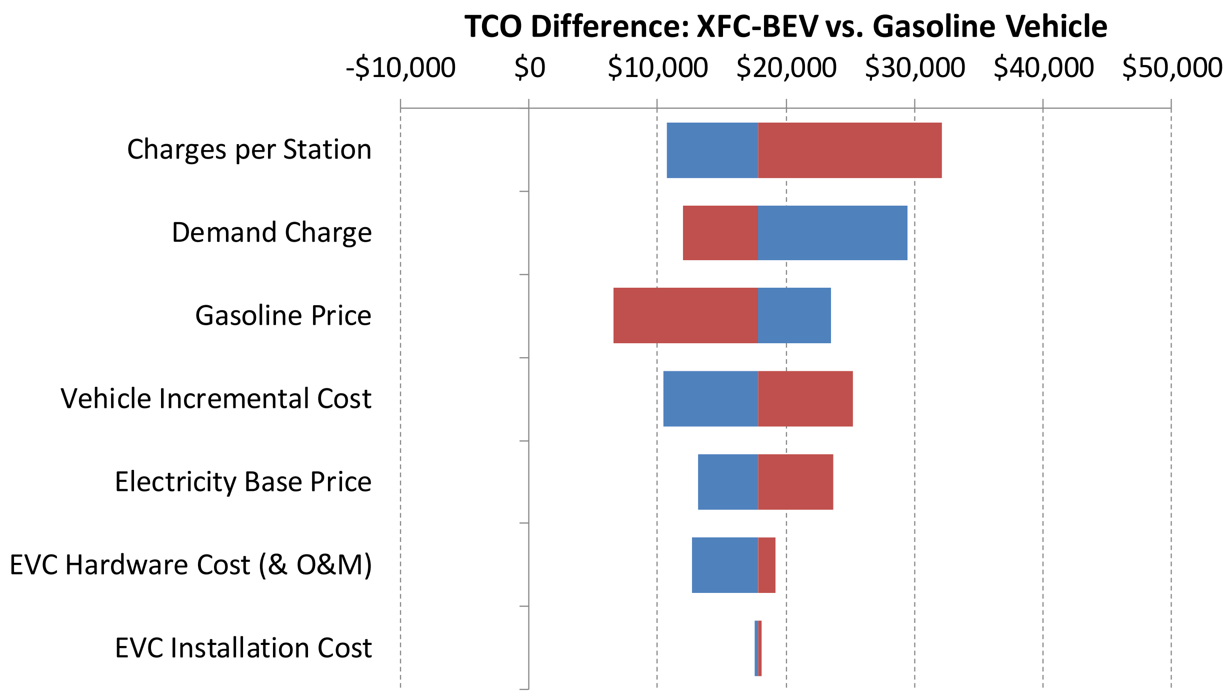

Figure 6: Passenger vehicle 15 year total cost of ownership based on vehicle propulsion system configuration.

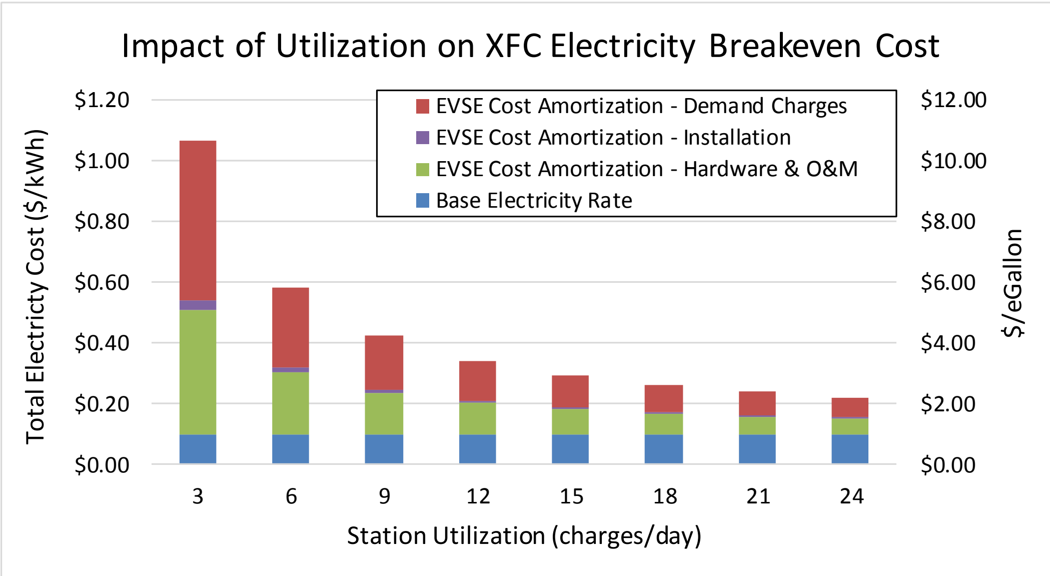

Table 1. Summary of key inputs for ICEV, HEV, and BEV TCO analysis for a single XFC port

	All	ICEV	HEV	DCFC-BEV	XFC-BEV
Fuel Economy (MPGGE)		33.0	46.1	115.4	115.4
CD Electricity Use (kWh/100mi)				28.5	28.5
Purchase Price ($/Vehicle)		$20,000	$23,000	$35,000	$36,000
Vehicle Lifetime (yr)	15				
Vehicle Annual (mileage)	12,400				
EVSE Hardware Cost				$30,000	$245,000
EVSE Installation Cost				$33,000	$41,000
Demand Charge ($/kW/month)				$8	$8
Charging Time (min/user)				80	10
Charge Sessions (#/day)				5	12
EVSE Charging Power (kW)				50	400
EVSE Efficiency (%)				92%	90%
EVSE DC Electricity Dispensed (kWh/session)				67	67
Gasoline Price ($/gal)	$3.00				
Base Electricity Rate ($/kWh)				$0.10	$0.10
EVSE Cost Amortization ($/kWh)				$0.09	$0.24
Total Electricity Cost ($/kWh)				$0.19	$0.34
Value of Time Travel Savings ($/hr)	$25				
Gasoline Fueling Rate (gal/min)	10				
Vehicle Lifetime (hours fueling)		9	7	1060	133

Table 2. Summary of sensitivity cases for TCO analysis with costs based on a single XFC port

Parameter	Units	Inputs-Low	Inputs-Default	Inputs-High
Charges per Station	#/day	6	12	24
Demand Charge	$/kW	$2	$8	$20
Gasoline Price	$/gal	$2	$3	$5
Vehicle Incremental Cost	$	$8,000	$16,000	$24,000
Electricity Base Price	$/kWh	$0.02	$0.10	$0.20
XFC Hardware Cost	$	$35,000	$245,000	$300,000
XFC Installation Cost	$	$20,000	$41,000	$60,000